AGU PUBLICATIONS

Geophysical Research Letters

RESEARCH LETTER

10.1002/2016GL067818

Ocean temperature thresholds for Last Interglacial West Antarctic Ice Sheet collapse

Johannes Sutter[1], Paul Gierz[1], Klaus Grosfeld[1], Malte Thoma[1], and Gerrit Lohmann[1,2]

[1]Paleoclimate Dynamics, Alfred Wegener Institute for Polar and Marine Research, Bremerhaven, Germany, [2]MARUM-Center for Marine Environmental Sciences, University of Bremen, Bremen, Germany

Key Points:
- Southern Ocean temperature thresholds of 2–3°C for LIG WAIS collapse
- Twin peak Antarctic Last Interglacial sea level contribution
- Potential future WAIS dynamics range from moderate retreat to complete collapse

Supporting Information:
- Text S1 and Figures S1–S14

Correspondence to:
J. Sutter,
johannes.sutter@awi.de

Citation:
Sutter, J., P. Gierz, K. Grosfeld, M. Thoma, and G. Lohmann (2016), Ocean temperature thresholds for Last Interglacial West Antarctic Ice Sheet collapse, *Geophys. Res. Lett.*, *43*, 2675–2682, doi:10.1002/2016GL067818.

Received 15 JAN 2016
Accepted 26 JAN 2016
Accepted article online 28 JAN 2016
Published online 29 MAR 2016

Abstract The West Antarctic Ice Sheet (WAIS) is considered the major contributor to global sea level rise in the Last Interglacial (LIG) and potentially in the future. Exposed fossil reef terraces suggest sea levels in excess of 7 m in the last warm era, of which probably not much more than 2 m are considered to originate from melting of the Greenland Ice Sheet. We simulate the evolution of the Antarctic Ice Sheet during the LIG with a 3-D thermomechanical ice sheet model forced by an atmosphere-ocean general circulation model (AOGCM). Our results show that high LIG sea levels cannot be reproduced with the atmosphere-ocean forcing delivered by current AOGCMs. However, when taking reconstructed Southern Ocean temperature anomalies of several degrees, sensitivity studies indicate a Southern Ocean temperature anomaly threshold for total WAIS collapse of 2–3°C, accounting for a sea level rise of 3–4 m during the LIG. Potential future Antarctic Ice Sheet dynamics range from a moderate retreat to a complete collapse, depending on rate and amplitude of warming.

1. Introduction

The Last Interglacial (LIG) climate at about 125 kyr B.P. is considered to be warmer than most of the Holocene and a time with considerably smaller ice sheets than today. Proxy evidence suggests global sea levels about 7 m higher than present day [*Kopp et al.*, 2013; *Dutton et al.*, 2015], of which only approximately 3 m are covered by contributions from ocean thermal expansion *McKay et al.* [2011], land-based glaciers (both 0.5 m) [*Marzeion et al.*, 2012], and melting of the Greenland Ice Sheet (2 m) [*Dahl-Jensen et al.*, 2013]. The remaining 4 m must therefore be derived from a mass loss from the Antarctic Ice Sheet. Observations and modeling studies of the present and future East Antarctic Ice Sheet present a mixed picture of potential growth [*Harig and Simons*, 2015] or partial collapse unfolding over several millennia [*Mengel and Levermann*, 2014]. The marine sections of the WAIS have the potential to raise global sea level by more than 3 m [*Bamber et al.*, 2009] and, being prone to marine ice sheet instability [*Schoof*, 2007] (MISI) potentially triggered by warming of surface [*Mercer*, 1978] and ocean temperatures [*Joughin and Alley*, 2011], are the prime suspects for LIG sea level contribution. It has been pointed out that WAIS collapse could be initiated by increased melting at the base of the ice shelves, which buttress their tributary glaciers and exert a backpressure force on the ice streams and outlet glaciers of the hinterland [*Scambos et al.*, 2004]. A reduction of this buttressing effect caused by ice shelf retreat would lead to an acceleration of the glaciers, draining more and more ice into the ocean. Further, a grounding line situated on inland downward sloping bedrock is inherently unstable [*Schoof*, 2007]; thus, an initial grounding line retreat caused by increased basal melting underneath the ice shelves could push the WAIS into a configuration where a runaway retreat due to the MISI is triggered. Recent publications are indicative of an ongoing or future MISI in the Amundsen Sea sector [*Rignot et al.*, 2014; *Joughin et al.*, 2014]; however, uncertainties embodied in ice sheet model simulations as well as the short window of in-depth glaciological observations prohibit conclusive findings as yet. Observations and modeling studies show melt rates in excess of several tens of meters per year underneath the ice shelves in this region during the last decades [*Jacobs et al.*, 2011]. In addition, analyses of boreholes drilled through Whillans Ice Stream (Ice Stream B) at the Siple Coast (see supporting information Figure S7) have found marine diatoms indicative of an open marine environment in the Ross embayment in the late Pleistocene [*Scherer et al.*, 1998] (probably during marine oxygen isotope stage 11). Warming of Southern Ocean temperatures could have led to a complete or partial WAIS collapse during the LIG as well, explaining the high sea levels found in reconstructions. Here we will investigate potential climatological thresholds which could initiate WAIS collapse in the LIG and future millennia.

2. Methods

In this study, we examine the dynamic behavior of the Antarctic Ice Sheet in transient model simulations, spanning the LIG utilizing a continental scale three-dimensional Ice Sheet Model (ISM) [*Thoma et al.*, 2014]. All simulations are carried out on a 40 × 40 km regular grid with 41 vertical sigma layers, covering the whole Antarctic Ice Sheet. The coarse resolution was chosen to allow for extensive exploration of the parameter space spanned by the basal friction and shelf melt rate coefficient. Since we resolve subgrid grounding line positions with a simple interpolation scheme, we validate sufficient model sensitivity to the applied climate forcing by testing our ISM in a model setting adapting the basal melt rate parameterization applied in *Pollard and DeConto* [2009] and simulate comparable grounding line migration in an extreme interglacial setting (see Figure S9). This gives us confidence that sheet/shelf dynamics are comparably resolved on long time scales, coarse resolution, and lack of a more sophisticated grounding line treatment notwithstanding. Basal melt rates underneath the shelf are simulated based on the method described by *Beckmann and Goosse* [2003] and match the total Antarctic shelf melt rate for present-day conditions [*Depoorter et al.*, 2013]. To capture the complex interactions and nonlinearities in the climate system, we force the ISM with climate time slice output of an atmosphere-ocean general circulation model (AOGCM) Community Earth System Models (COSMOS) [*Lunt et al.*, 2013; *Pfeiffer and Lohmann*, 2015] for the LIG (for a more detailed overview of the COSMOS simulations see supporting information and Figures S1 and S2). Resolution and spin-up time of the COSMOS simulations are similar to what has been utilized in *Lunt et al.* [2013], *Pfeiffer and Lohmann* [2015], and *Gierz et al.* [2015]. Transient forcing is realized by interpolating between the LIG climate time slice and present-day climate with the glacial index method, where the glacial index is derived from Dome C deuterium depletion [*Jouzel et al.*, 2007; *Stenni et al.*, 2010] (Figure 1a). Deuterium depletion measured in ice cores is widely used as a proxy for local past temperature changes [*Jouzel and Masson-Delmotte*, 2007]. The temperature variations recorded in an ice core can be used to reconstruct the long-term climate variations in the region. The climate forcing at any given time during the simulations is calculated (here shown with surface temperature) as

$$T^{i,j}_{\mathrm{surf}}(t) = T^{i,j}_{\mathrm{surf}}(\mathrm{LIG}) \cdot \frac{\delta(t) - \delta_{\mathrm{PD}}}{1 - \delta_{\mathrm{PD}}} + T^{i,j}_{\mathrm{surf}}(\mathrm{PD}) \cdot \frac{1 - \delta(t)}{1 - \delta_{\mathrm{PD}}} \tag{1}$$

where $T^{i,j}$ denotes the temperature at node i, j; $\delta(t)$ the normalized Deuterium value at time t; and $\delta_{(PD)}$ the normalized present-day mean Deuterium value. Experiments E and Eg (see Appendix) depict the two different LIG climatologies simulated with our AOGCM, which exhibit significant differences in accumulation (E slight reduction, Eg ∼20% increase) and Southern Ocean subsurface temperatures (E slight cooling, Eg ∼0.5°C warming; see supporting information Figures S1 and S2). Using this forcing, we carry out transient simulations with our ISM from 131.5 to 118 kyr B.P. (see Appendix). Antarctic sea level contribution is calculated by accounting for the water equivalent volume above floatation for marine ice sheets and the volume changes of the ice sheets grounded above sea level via the formula

$$\frac{V^0_{\mathrm{afb}} - V^f_{\mathrm{afb}}}{A_O} = \mathrm{SLE}\,(m) \tag{2}$$

where V^0_{afb} is the initial volume above floatation, V^f_{afb} is the final volume above floatation, and A_O is the global ocean area. The effect of bedrock relaxation due to reduced ice loads is accounted for.

3. Results

3.1. Stable WAIS Under GCM Forcing

In the associate transient experiments (denoted as E0 and Eg0), the ice dynamics and mass balance are not significantly affected compared to the control run (Figure 1b, blue and green lines). While the subsurface Southern Ocean warming is considerable in Eg, which might be caused by a weakened Atlantic Meridional Overturning Circulation (AMOC) due to freshwater perturbations from Greenland meltwater [*Gierz et al.*, 2015] and a subsequent warming of the Southern Ocean by means of the bipolar seesaw effect [*Barker et al.*, 2009], it is not sufficient to trigger any destabilization of WAIS. An increased surface mass balance in Eg even leads to an overall increase of Antarctic ice volume and a sea level drop by about 0.5 m at midinterglacial (Figure 1b). Comparison to proxy data [*Capron et al.*, 2014; *Rosenthal et al.*, 2013] of LIG ocean temperature anomalies indicates that the AOGCM underestimates Southern Ocean temperature anomalies by several degrees. Proxy and climate modeling evidence suggests an intensification of the hydrological cycle accompanying climate

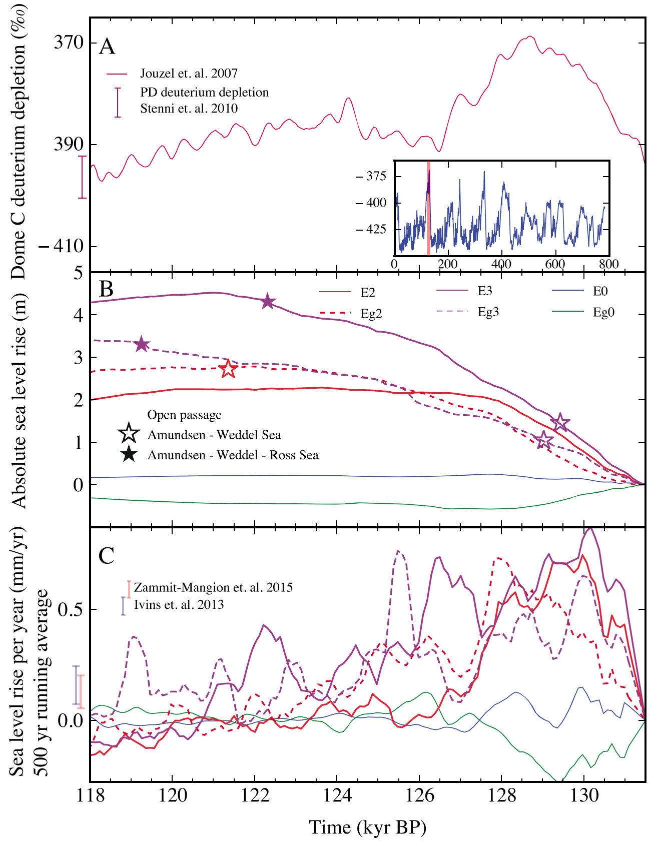

Figure 1. (a) Deuterium depletion from Dome C ice core [*Jouzel et al.*, 2007]; the inlay shows the complete record (with the highlighted section marking the LIG, time axis in kyr). The present-day mean deuterium depletion at the ice core site [*Stenni et al.*, 2010] is depicted by the red bar next to the graph. Please note that the time axis runs from right (past) to left (present). (b) Simulated Antarctic contribution to sea level rise. Simulations with 2 and 3° Southern Ocean temperature anomalies are shown (results for 1° not shown here, supporting information Figures S5 (Eg1) and S8 (E1)). The stars indicate the points in time at which partial (open) or complete (filled) WAIS collapse is reached. (c) The corresponding sea level rise rates in mm/yr (500 year running mean). The two bars next to the graph depict observed present-day Antarctic sea level contributions. Complete collapse is modeled in E3 and Eg3. Partial collapse is already reached at 2° ocean warming for scenario Eg2.

warming, carrying more humidity to the AIS, hence increasing the snowfall over the continent. Such an intensification (resembled in experiment Eg) would increase the ice volume and lower the sea level. The moderate increases in surface temperatures preclude a major effect of surface melting or fabric softening of the ice matrix which would lead to faster ice flow and discharge into the ocean. This line of reasoning leaves only Southern Ocean warming as the most probable candidate for triggering the MISI in the LIG. A potential source of additional subsurface Southern Ocean warming during the LIG could be, e.g., a reduced Southern Ocean overturning circulation caused by ice-ocean interactions [*Golledge et al.*, 2014; *Weber et al.*, 2014].

3.2. Ocean Temperature Thresholds for WAIS Collapse

In order to analyze the full sensitivity range of the WAIS during the LIG, we apply uniform ocean temperature anomalies of 1 to 3°C (compared to present-day observations) combined with the surface climate of E and Eg. The corresponding transient experiments are denoted as E1, E2, and E3 and Eg1, Eg2, and Eg3 and are shown in Figures 1b and 1c. Our results suggest a temperature threshold for a complete decay of the WAIS between 2°C and 3°C, which is within a conceivable range of estimated Southern Ocean temperature anomalies derived from proxy data [*Capron et al.*, 2014; *Rosenthal et al.*, 2013]. WAIS collapse manifests in a nonlinear fashion, initialized by a complete melt of the major ice shelves in the Ross and Weddell Seas (taking about 500 years; see supporting information Figures S3–S6). Due to the loss of buttressing and sustained melting close to the grounding line, the ice shelves tributary glaciers draining central West Antarctica accelerate and discharge increasing amounts of grounded ice into the sea. Thinning of the coastal ice sheet leads to floatation and subsequent grounding line retreat (Figure 2a), resulting in rates of sea level rise in

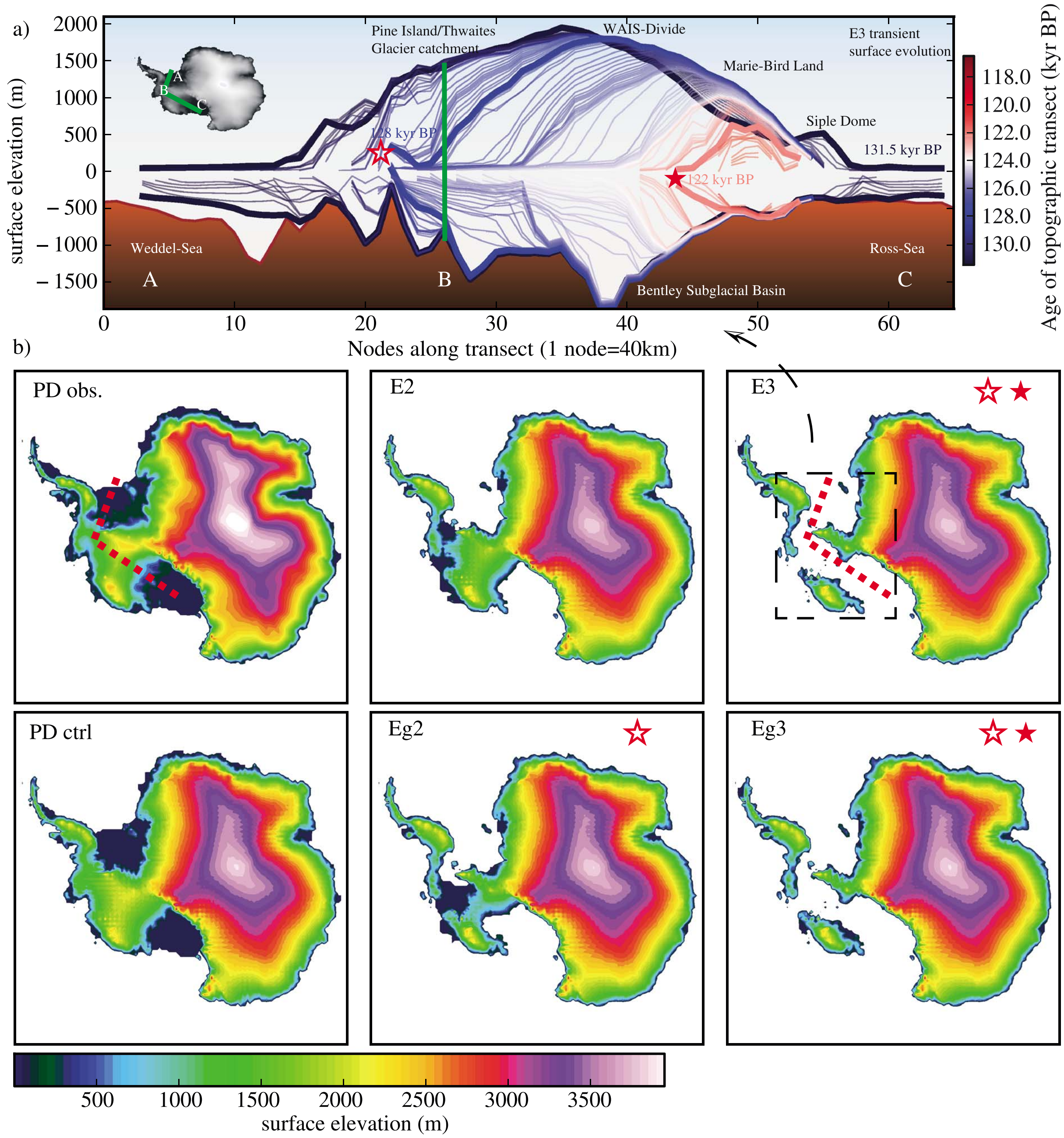

Figure 2. (a) Transect across the West Antarctic Ice Sheet (WAIS) showing the transient evolution of the surface topography during simulation E3. Each transect line illustrates a snapshot during the LIG (one snapshot every 100 years). Several semistable grounding line positions are visible around inland ascending bedrock slopes. Thick transect lines depict the time at which partial or complete collapse of WAIS is reached, defined by the opening of ocean gateways between the Weddell and Amundsen Seas and subsequently the Ross Sea (identified as in Figure 1b by stars). Inlay shows transect location from the Weddell Sea (A) to the Ross Sea (C). (b) Surface topographies at the end of each simulation (PD observations, E2 ocean anomaly, E3, PD ctrl, Eg2, Eg3). Dark blue areas depict ice shelves. The transect from Figure 2a is again depicted by the red dashed line in the first and third surface topography box (PD observations and E3).

excess of 1 mm/yr averaged over 100 years (Figure 1c), a multifold increase compared with present-day contributions of the Antarctic Ice Sheet [*Zammit-Mangion et al.*, 2015; *Ivins et al.*, 2013]. This high sea level rise is sustained until circa 129 kyr B.P. (E3 and Eg3) (Figure 1c) and is followed by a slowdown of ice loss rate, owing to the large remaining ice dome centered at the WAIS divide. At this point an open sea passage between the Weddell Sea and Amundsen Sea has been established (Figure 2a and supporting information Figures S3–S6). Driven by large surface topography gradients, surface velocities of the remaining ice dome increase, leading to thinning and the conversion of grounded ice into ice shelves. As the grounding line retreats toward the steep reverse bedrock slopes of the Byrd Subglacial Basin (Figure 2a and supporting information Figure S10), the ice sheet approaches yet another unstable configuration. Warm waters entering from the Amundsen Sea intrude into the opening ocean gateway, melting the newly formed ice shelf, thereby accelerating the second phase of ice loss and grounding line retreat which again culminates in sea level rise of up to 1 mm/yr in E3 and Eg3 around 126.5 and 125.5 kyr B.P., respectively (Figure 1c).

3.3. Twin Peak Sea Level Rise

This evolution, controlled by a combination of the MISI, warm subsurface ocean temperatures, and variations in surface accumulation, leads to a distinctive double peak in sea level rise contribution of the WAIS in the LIG (Figure 1c). A potential subsurface ocean-temperature-cooling episode, flanked by increases in the surface mass balance, might lead to a recovery in ice volume between the two stages of collapse shown in our simulations, which could explain the previously suggested double peak in LIG sea level high stand [*Kopp et al.*, 2013] (Northern Hemisphere ice sheet evolution might exacerbate this effect).

3.4. Further Climatological Drivers

Driven by ocean temperature warming, the collapse of WAIS is strongly modulated by the surface mass balance leading to differences in sea level rise of more than 1 m between simulations E3 and Eg3 (Figure 1b). The higher surface mass balance in Eg3 leads to a reduction of sea level rise. However, the increased accumulation in Eg can lead to higher surface gradients, favoring faster ice discharge [*Winkelmann et al.*, 2012]. In the case of Eg2 this leads to a partial collapse of the WAIS and 0.5 m higher sea level compared with E2. A retreat of the WAIS as simulated in this study leads to the opening of large open areas which would increase ocean surface temperatures due to absorption of solar radiation. Atmospheric cooling due to changes in the cyclonic circulation [*Steig et al.*, 2015] could dampen this warming. Additionally, the seasonal cycle of sea ice in the newly formed West Antarctic ocean ranges would influence ocean circulation. However, such atmospheric and ocean feedback effects induced by dramatic changes in the ice geometry cannot be captured yet since fully coupled atmosphere-ice-ocean GCMs are not available at this stage.

3.5. Future Antarctic Dynamics

A main difference between the climate change in the LIG and projected future warming is the faster projected ocean/atmosphere warming rate. To assess the future evolution of the Antarctic Ice Sheet, we apply our methodology to an idealized future scenario based on extreme warming projections of the Intergovernmental Panel on Climate Change (Representative Concentration Pathway (RCP) 8.5 [*Stocker et al.*, 2013]), similar to *Golledge et al.* [2015]. We assume a simple warming ramp peaking at a uniform 2 or 3°C warming of the Southern Ocean within 200 years accompanied by an atmospheric surface temperature warming of 6°C together with an increase in accumulation between 10 and 40% compared with the present-day surface mass balance. Such a rapid warming triggers an accelerated retreat of the West Antarctic Ice Sheet, gradually raising eustatic sea level up to 1 and 2 m by the year 3000 and up to 4 m by the year 5000 (Figure 3a) which surpasses the potential contribution of WAIS, indicative of an increased discharge from East Antarctica. To investigate the stability of the WAIS in a hypothetical extreme warming scenario in which the Antarctic ice shelves collapse within a century, we subject the Filchner-Ronne and Ross Ice Shelves to a strong negative mass balance (prescribed by a melting rate underneath the shelves of approximately 40 m/a) mimicking the modeling setup applied by *Pollard et al.* [2015] or the extreme forcings prescribed in *Winkelmann et al.* [2015]. This culminates in ice shelf disintegration within several decades and leads to the total collapse of the WAIS within this millennium accompanied by an Antarctic contribution to sea level rise in excess of 0.5 m per century and a long-term sea level rise larger than 5 m (Figure 3). We note that the coarse resolution applied in our modeling setup prevents an adequate representation of the Marine Ice Sheet in Wilkes Land (East Antarctica), which has been shown to be prone to the MISI triggered by sustained ice shelf melting in previous studies [*Fogwill et al.*, 2014; *Mengel and Levermann*, 2014] and would raise global sea level by an additional 3 to 4 m if completely collapsed. We point out, however, that a rapid WAIS collapse within this millennium is at the far end of conceivable future West Antarctic Ice Sheet dynamics, only triggered in extreme warming scenarios. Such conditions could be reached if future greenhouse gas emissions follow a business as usual path as laid out by the RCP8.5 scenario [*Stocker et al.*, 2013]. *Trusel et al.* [2015] show that this could subject most Antarctic ice shelves to surface melt rates which have been associated with rapid ice shelf collapse in the Antarctic Peninsula (the collapse of the Larsen A and B ice shelves).

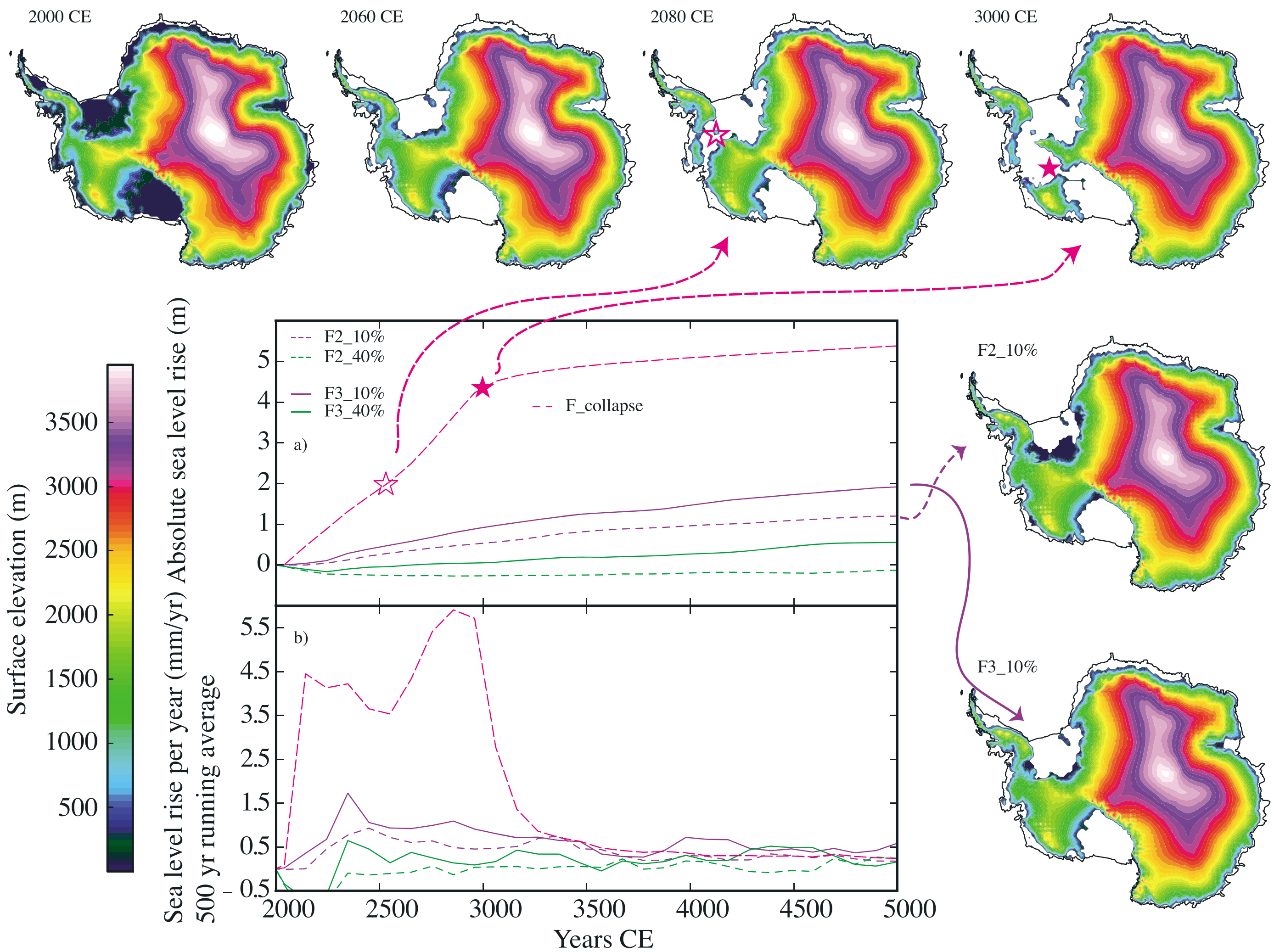

Figure 3. WAIS evolution in our idealized future warming scenarios. (a) All simulations follow a 200 year warming ramp initiated in the year 2000. Peak warming is reached in the year 2200 (e.g., +2° ocean warming, +6° surface air temperature, and 10% precipitation increase (2°_10%).) In the simulation F_collapse high melt rates are prescribed to disintegrate all ice shelves within the next century (the stars identify the timing of partial and complete WAIS collapse from Figure 1b). (b) Corresponding sea level rise per year for above simulations. The upper horizontal row depicts the evolution of the surface topography for the rapid ice shelf collapse scenario. The vertical row maps the ice sheet topography after 1 kyr for Experiments 2°_10% and 3°_10%. The black line in the surface elevation maps approximates the present-day extent of the Antarctic Ice Sheet.

4. Discussion

In summary, our simulations show that in the LIG as well as in the future, strong subsurface Southern Ocean warming is essential to destabilize the West Antarctic Ice Sheet. The double peak in sea level rise observed in our simulations hints at a two-phase WAIS collapse due to its characteristic topographic and bathymetric features. A more detailed investigation regarding this double peak could reveal a crucial role of the WAIS in the twin peak sea level highstand suggested by *Kopp et al.* [2013]. Melting at the base of Antarctic ice shelves is largely driven by warm modified deep water, which enters the shelf cavity along deep bathymetric channels [*Schmidtko et al.*, 2014], a process just recently simulated in high-resolution ocean models [*Hellmer et al.*, 2012]. Our results call for the representation of these bathymetric warm water pathways in future large-scale GCM climate models coupled to ice sheet dynamics. This study shows that a Southern Ocean temperature regime corresponding to the extreme end of paleoreconstructions in the LIG could have pushed the WAIS into a configuration where the MISI instability and runaway retreat is triggered, reconciling a LIG sea level highstand around 7 m caused by melting of Greenland and Antarctica. The future evolution of the Antarctic Ice Sheet hinges on both the amplitude and the rate of ocean and surface warming, leaving a large event horizon between rapid collapse and moderate retreat.

Acknowledgments
This study is promoted by Helmholtz funding through the Polar Regions and Coasts in the Changing Earth System (PACES) program of the AWI. Funding by the graduate school ESSReS and the Helmholtz Climate Initiative REKLIM is gratefully acknowledged. Model output and data are available upon request. We thank M. Pfeiffer for providing output of the AOGCM experiment Eg.

References

Bamber, J. L., R. E. M. Riva, B. L. A. Vermeersen, and A. M. LeBrocq (2009), Reassessment of the potential sea-level rise from a collapse of the West Antarctic Ice Sheet, *Science*, *324*(5929), 901–903.

Barker, S., P. Diz, M. J. Vautravers, J. Pike, G. Knorr, I. R. Hall, and W. S. Broecker (2009), Interhemispheric Atlantic seesaw response during the last deglaciation, *Nature*, *457*(7233), 1097–1102.

Beckmann, A., and H. Goosse (2003), A parameterization of ice shelf-ocean interaction for climate models, *Ocean Modell.*, *5*(2), 157–170.

Capron, E., A. Govin, E. J. Stone, V. Masson-Delmotte, S. Mulitza, B. Otto-Bliesner, T. L. Rasmussen, L. C. Sime, C. Waelbroeck, and E. W. Wolff (2014), Temporal and spatial structure of multi-millennial temperature changes at high latitudes during the Last Interglacial, *Quat. Sci. Rev.*, *103*, 116–133.

Dahl-Jensen, D., et al. (2013), Eemian interglacial reconstructed from a Greenland folded ice core, *Nature*, *493*(7433), 489–494.

Depoorter, M. A., J. L. Bamber, J. A. Griggs, J. T. M. Lenaerts, S. R. M. Ligtenberg, M. R. van den Broeke, and G. Moholdt (2013), Calving fluxes and basal melt rates of Antarctic ice shelves, *Nature*, *502*(7469), 89–93.

Dutton, A., J. M. Webster, D. Zwartz, K. Lambeck, and B. Wohlfarth (2015), Tropical tales of polar ice: Evidence of Last Interglacial polar ice sheet retreat recorded by fossil reefs of the granitic Seychelles Islands, *Quat. Sci. Rev.*, *107*, 182–196.

Fogwill, C. J., C. S. M. Turney, K. J. Meissner, N. R. Golledge, P. Spence, J. L. Roberts, M. H. England, R. T. Jones, and L. Carter (2014), Testing the sensitivity of the East Antarctic Ice Sheet to Southern Ocean dynamics: Past changes and future implications, *J. Quat. Sci.*, *29*(1), 91–98.

Gierz, P., G. Lohmann, and W. Wei (2015), Response of Atlantic overturning to future warming in a coupled atmosphere-ocean-ice sheet model, *Geophys. Res. Lett.*, *42*, 6811–6818, doi:10.1002/2015GL065276.

Golledge, N. R., L. Menviel, L. Carter, C. J. Fogwill, M. H. England, G. Cortese, and R. H. Levy (2014), Antarctic contribution to meltwater pulse 1A from reduced Southern Ocean overturning, *Nat. Commun.*, *5*, 5107.

Golledge, N. R., D. E. Kowalewski, T. R. Naish, R. H. Levy, C. J. Fogwill, and E. G. W. Gasson (2015), The multi-millennial Antarctic commitment to future sea-level rise, *Nature*, *526*(7573), 421–425.

Harig, C., and F. J. Simons (2015), Accelerated West Antarctic ice mass loss continues to outpace East Antarctic gains, *Earth Planet. Sci. Lett.*, *415*, 134–141.

Hellmer, H. H., F. Kauker, R. Timmermann, J. Determann, and J. Rae (2012), Twenty-first-century warming of a large Antarctic ice-shelf cavity by a redirected coastal current, *Nature*, *485*(7397), 225–228.

Ivins, E. R., T. S. James, J. Wahr, E. J. O. Schrama, F. W. Landerer, and K. M. Simon (2013), Antarctic contribution to sea level rise observed by GRACE with improved GIA correction, *J. Geophys. Res. Solid Earth*, *118*, 3126–3141, doi:10.1002/jgrb.50208.

Jacobs, S. S., A. Jenkins, C. F. Giulivi, and P. Dutrieux (2011), Stronger ocean circulation and increased melting under Pine Island Glacier ice shelf, *Nat. Geosci.*, *4*(8), 519–523.

Joughin, I., and R. B. Alley (2011), Stability of the West Antarctic Ice Sheet in a warming world, *Nat. Geosci.*, *4*(8), 506–513.

Joughin, I., B. E. Smith, and B. Medley (2014), Marine Ice Sheet collapse potentially under way for the Thwaites Glacier Basin, West Antarctica, *Science*, *344*(6185), 735–738.

Jouzel, J., and V. Masson-Delmotte (2007), ICE CORE RECORDS—Antarctic stable isotopes, in *Encyclopedia of Quaternary Science*, edited by S. A. Elias, pp. 1242–1250, Elsevier, Oxford, U. K.

Jouzel, J., et al. (2007), Orbital and millennial Antarctic climate variability over the past 800,000 years, *Science*, *317*(5839), 793–796.

Kopp, R. E., F. J. Simons, J. X. Mitrovica, A. C. Maloof, and M. Oppenheimer (2013), A probabilistic assessment of sea level variations within the last interglacial stage, *Geophys. J. Int.*, *193*(2), 711–716.

Lunt, D. J., et al. (2013), A multi-model assessment of last interglacial temperatures, *Clim. Past*, *9*(2), 699–717.

Marzeion, B., A. H. Jarosch, and M. Hofer (2012), Past and future sea-level change from the surface mass balance of glaciers, *Cryosphere*, *6*(6), 1295–1322.

McKay, N. P., J. T. Overpeck, and B. L. Otto-Bliesner (2011), The role of ocean thermal expansion in Last Interglacial sea level rise, *Geophys. Res. Lett.*, *38*, L14605, doi:10.1029/2011GL048280.

Mengel, M., and A. Levermann (2014), Ice plug prevents irreversible discharge from East Antarctica, *Nat. Clim. Change*, *4*(6), 451–455.

Mercer, J. H. (1978), West Antarctic Ice Sheet and CO_2 greenhouse effect—Threat of disaster, *Nature*, *271*(5643), 321–325.

Pfeiffer, M., and G. Lohmann (2015), Greenland Ice Sheet influence on Last Interglacial climate: Global sensitivity studies performed with an atmosphere-ocean general circulation model, *Clim. Past Discuss.*, *11*(2), 933–995.

Pollard, D., and R. M. DeConto (2009), Modelling West Antarctic ice sheet growth and collapse through the past five million years, *Nature*, *458*, 329–333.

Pollard, D., R. M. DeConto, and R. B. Alley (2015), Potential Antarctic Ice Sheet retreat driven by hydrofracturing and ice cliff failure, *Earth Planet. Sci. Lett.*, *412*, 112–121.

Rignot, E., J. Mouginot, M. Morlighem, H. Seroussi, and B. Scheuchl (2014), Widespread, rapid grounding line retreat of Pine Island, Thwaites, Smith, and Kohler glaciers, West Antarctica, from 1992 to 2011, *Geophys. Res. Lett.*, *41*, 3502–3509, doi:10.1002/2014GL060140.

Rosenthal, Y., B. K. Linsley, and D. W. Oppo (2013), Pacific ocean heat content during the past 10,000 years, *Science*, *342*(6158), 617–621.

Scambos, T. A., J. A. Bohlander, C. A. Shuman, and P. Skvarca (2004), Glacier acceleration and thinning after ice shelf collapse in the Larsen B embayment, Antarctica, *Geophys. Res. Lett.*, *31*, L18402, doi:10.1029/2004GL020670.

Scherer, R. P., A. Aldahan, S. Tulaczyk, G. Possnert, H. Engelhardt, and B. Kamb (1998), Pleistocene collapse of the West Antarctic Ice Sheet, *Science*, *281*(5373), 82–85.

Schmidtko, S., K. J. Heywood, A. F. Thompson, and S. Aoki (2014), Multidecadal warming of Antarctic waters, *Science*, *346*(6214), 1227–1231.

Schoof, C. (2007), Ice sheet grounding line dynamics: Steady states, stability, and hysteresis, *J. Geophys. Res.*, *112*, F03S28, doi:10.1029/2006JF000664.

Steig, E. J., K. Huybers, H. A. Singh, N. J. Steiger, Q. Ding, D. M. W. Frierson, T. Popp, and J. W. C. White (2015), Influence of West Antarctic Ice Sheet collapse on Antarctic surface climate, *Geophys. Res. Lett.*, *42*, 4862–4868, doi:10.1002/2015GL063861.

Stenni, B., et al. (2010), The deuterium excess records of EPICA Dome C and Dronning Maud Land ice cores (East Antarctica), *Quat. Sci. Rev.*, *29*(1–2), 146–159.

Stocker, T., et al. (2013), Technical summary, in *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*, edited by T. F. Stocker et al., pp. 33–115, Cambridge Univ. Press, Cambridge, U. K., and New York.

Thoma, M., K. Grosfeld, D. Barbi, J. Determann, S. Goeller, C. Mayer, and F. Pattyn (2014), RIMBAY—A multi-approximation 3D ice-dynamics model for comprehensive applications: Model description and examples, *Geosci. Model Dev.*, *7*(1), 1–21.

Trusel, L. D., K. E. Frey, S. B. Das, K. B. Karnauskas, P. Kuipers Munneke, E. van Meijgaard, and M. R. van den Broeke (2015), Divergent trajectories of Antarctic surface melt under two twenty-first-century climate scenarios, *Nat. Geosci.*, *8*(12), 927–932.

Weber, M. E., et al. (2014), Millennial-scale variability in Antarctic Ice Sheet discharge during the last deglaciation, *Nature*, *510*(7503), 134–138.
Winkelmann, R., A. Levermann, M. A. Martin, and K. Frieler (2012), Increased future ice discharge from Antarctica owing to higher snowfall, *Nature*, *492*(7428), 239–242.
Winkelmann, R., A. Levermann, A. Ridgwell, and K. Caldeira (2015), Combustion of available fossil fuel resources sufficient to eliminate the Antarctic Ice Sheet, *Sci. Adv.*, *1*(8), e1500589.
Zammit-Mangion, A., J. Rougier, N. Schon, F. Lindgren, and J. Bamber (2015), Multivariate spatio-temporal modelling for assessing Antarctica's present-day contribution to sea-level rise, *Environmetrics*, *26*(3), 159–177.